An Upgraded Low-energy Muon Facility at Fermilab

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LOI: R. Bernstein et. al., https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF0-AF0-007.pdf

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Outline

- Motivation: Physics Opportunities
- FNAL Accelerator Complex
- PIP-II LE μ Facility
- Current LE μ Facilities
- Potential of heavy targets
- Muon Test Area R&D Facility
- Work Plan
- Summary

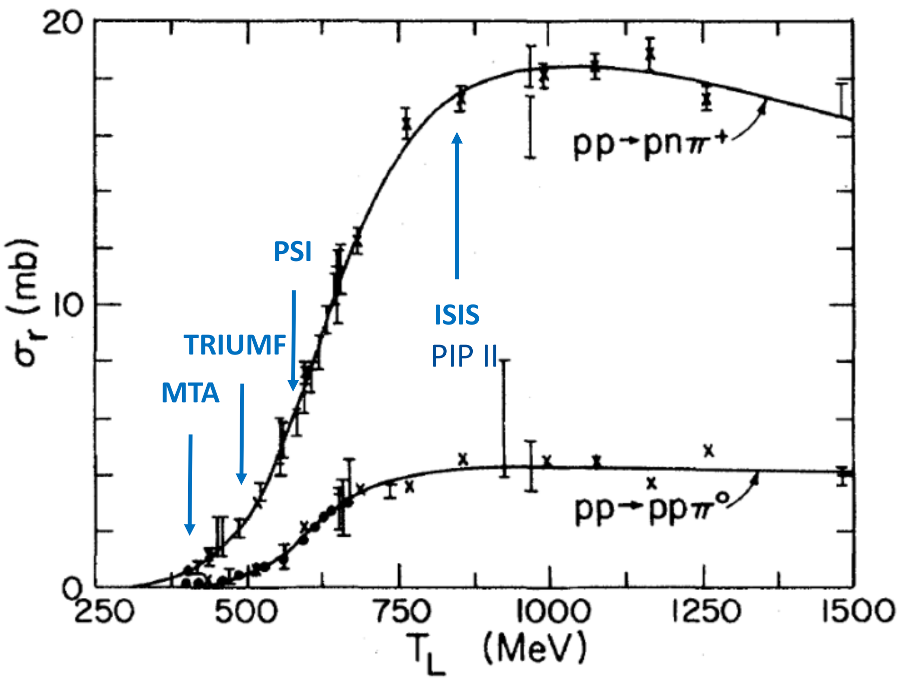
Physics Opportunities

- Low-energy muon (LEμ) experiments can address physics beyond Standard Model with very high sensitivity
  - *Do leptons violate flavor symmetry*
  - *Are there forces weaker than the Weak Force*
  - *Do antileptons experience gravity identically to leptons*
- Precision muon and muonium experiments are required
  - $g-2$ *and* $\mu \to e$ *conversion searches (Mu2e)*
  - *muon EDM,* $\mu \to e\gamma$ *and* $\mu \to 3e$ *searches (*μ^+ *or* μ^-*);*
  - *muonium gravity & spectroscopy (*μ^+*)*
- Other applications: (μ^+) μSR (Muon Spin Resonance) for materials science, chemistry, & biology; (μ^-) muon-cat. fusion
- LEμ experiments: synergistic, require intense muon beams

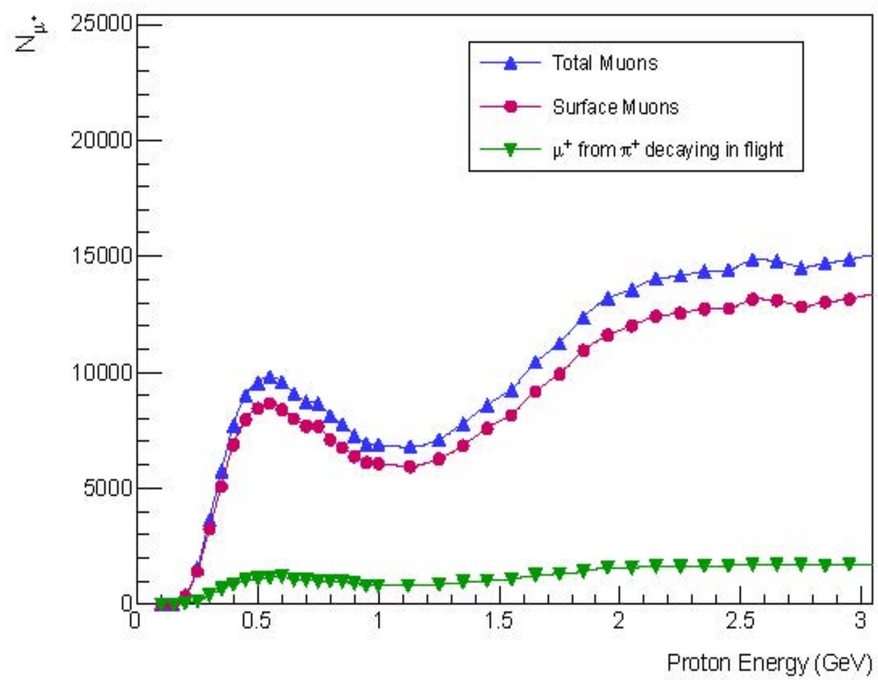
Physics Opportunities

Fermilab currently supports muon beams for $g-2$ & Mu2e:

- Generated by 8 GeV high-intensity protons
- Not optimal for low-energy muon production
- 800 MeV PIP II protons: unprecedented LEμ intensities

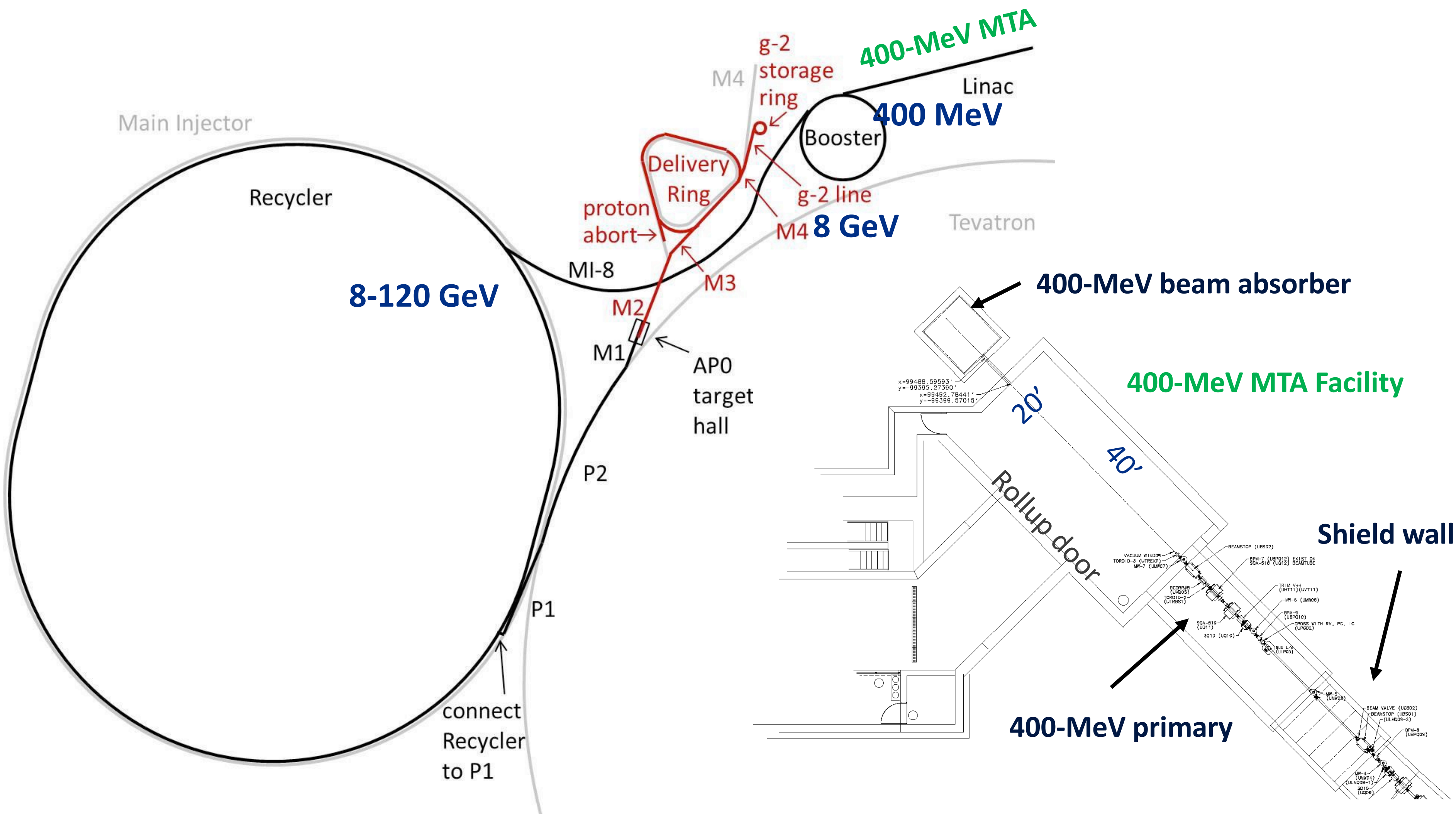


Total single pion production cross section dependence on proton energy



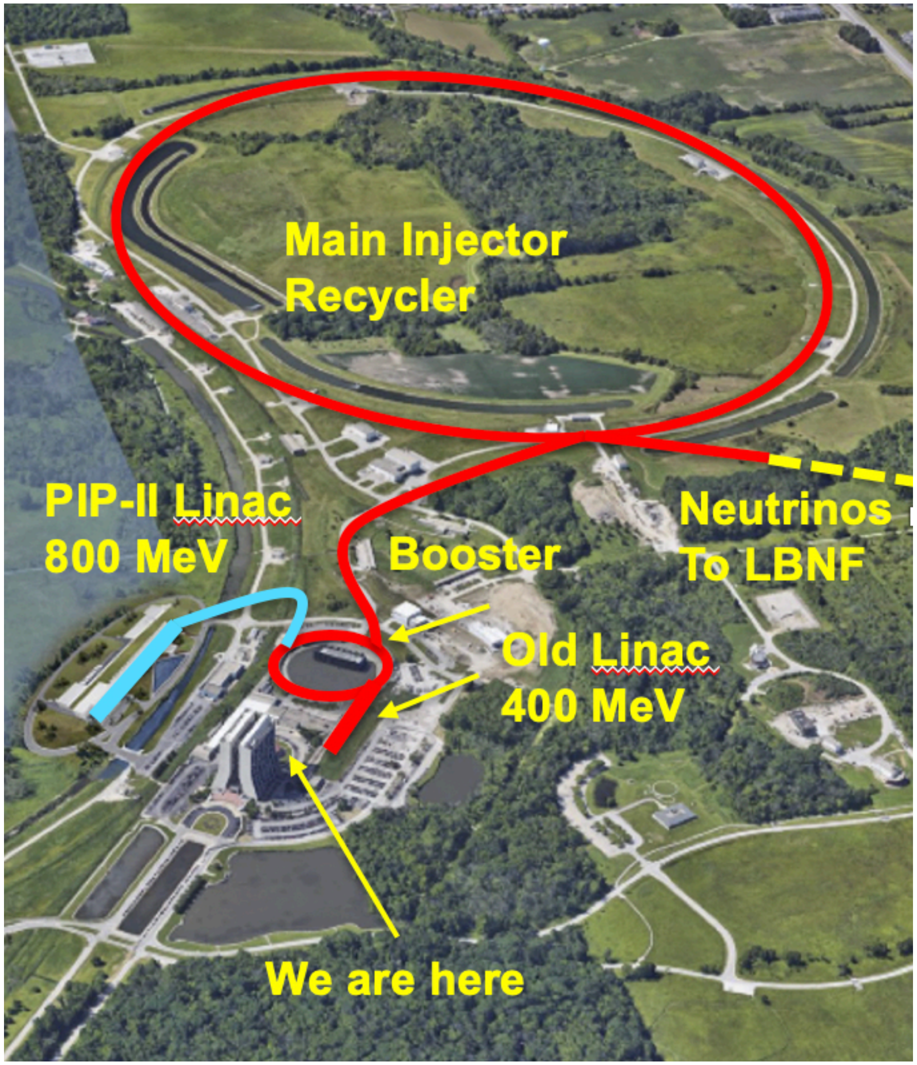
Variation of μ^+ yield with incident proton energy for muons with momenta ≤ 30 MeV/c; i.e. surface muons

Current Fermilab Accelerator Complex



Layout – HE muon beams supported in Delivery Ring & g-2; LE (≤100 MeV) muon beams at MTA facility and potentially at Mu2e exploiting available beamline & infrastructure.

Fermilab Accelerator Complex with PIP II Linac*

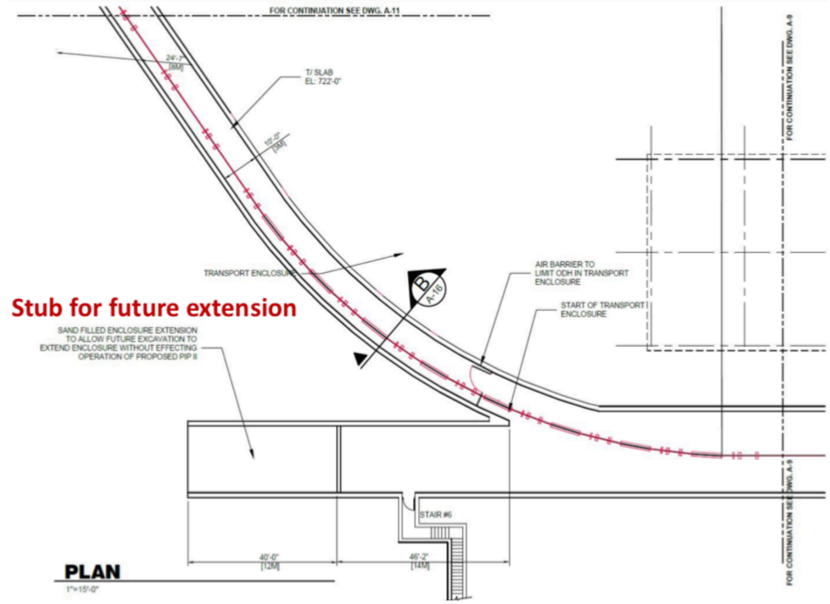


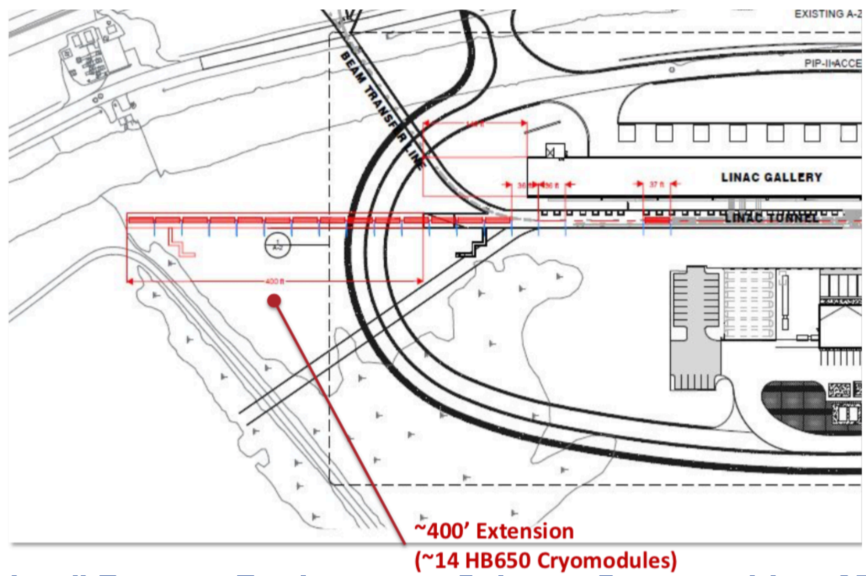
Delivered Beam Energy (kinetic)	**800 MeV**
Beam Particles	H^-
Beam Pulse Length	0.55 msec
Particles per Pulse	6.7×10^{12}
Pulse repetition Rate	20 Hz
Average Beam Current	2 mA
Bunch Intensity	1.9×10^{8}
Max Bunch Repetition Rate	162.5 MHz
Bunch Pattern	***Programmable***
RF Frequency	162.5 MHz and harmonics
Bunch Length (rms)	<4 psec
Transverse Emittance (rms, normalized)	≤0.3 mm-mrad
Longitudinal Emittance (rms)	≤0.35 mm-mrad (1.1 keV-nsec)

***E. Pozdeyev, "PIP II Linac and Possible Linac Extension," Booster Replacement Science Opportunities, 05/19/2020,**
https://indico.fnal.gov/event/23352/contributions/185568/attachments/128433/155375/Pozdeyev_PIP2_linac_200519.pptx

A new low-energy muon facility at PIP II

- **Beamline stub at end of PIP II is reserved for future 800-MeV to 2 GeV upgrade**
- **Available for "temporary" installation but no infrastructure plan.**
- **Eventual energy upgrade would remove facility**
- **Bending 2 GeV H^- beam to a new facility is particularly challenging**





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Existing LE Muon Facilities

- Current Muon Facilities are for MuSR (μ^+, < 30 MeV/c) and limited by
  - 4% IL graphite targets (spallation programs at PSI and ISIS)
  - $\leq$ 25% IL Be target at TRIUMF
  - light targets control primary beam divergence (small rad length)
  - CW intensity limited to ~1 surface muon/10 μsec
    - Need a "creation" timing signal, present only in pulsed beams

Table 1: Comparison of Surface Muon Facilities and Mu2e

Facility	Max. (surface) μ rate (Hz)	Type	Comments
PSI [14]	9×10^8	CW	
TRIUMF [15]	2×10^6	CW	
MuSIC at Osaka [16]	10^8	CW	
J-PARC [17]	6×10^7	pulsed	
ISIS [17]	6×10^5	pulsed	
HIMB at PSI [13]	10^{10}	CW	(design goal)
Mu2e at Fermilab	10^{11}	pulsed	Not surface muons: $p_\mu \approx 40\,\mathrm{MeV}/c$
Mu2e with PIP-II	10^{12}	pulsed	Not surface muons: $p_\mu \approx 40\,\mathrm{MeV}/c$

Pion Production however favors heavy targets

Production cross sections* for charged pions were measured using the 730-MeV proton beam from the 184″ LBNL cyclotron

- Total cross sections for π^+/π^- production beyond carbon to a good approximation are

$$\sigma_T(\pi^+) \approx 24.5\ Z^{1/3}\ \text{mb}$$

$$\sigma_T(\pi^-) \approx 2.33\ N^{2/3}\ \text{mb}$$

– *Heavier targets favor both π^+ and π^- as shown in Table*

– *Tantalum gives factor-3 (8) π^+ (π^-) increase over graphite*

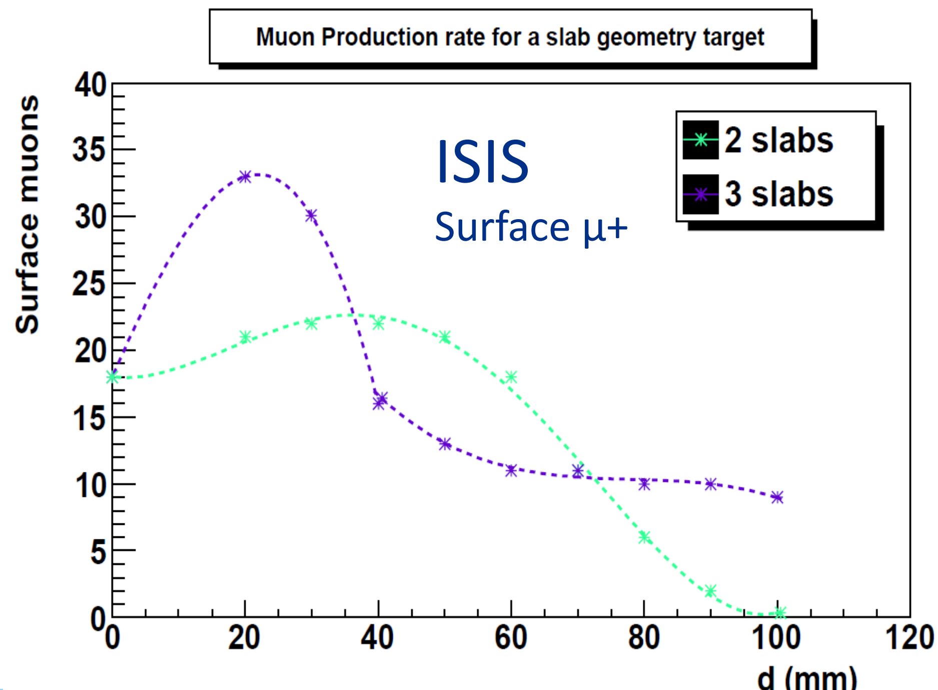
TABLE XII. Total cross sections for π^+ and π^-.

Element	σ^+	σ^-	Ratio
H	13.50±0.73	0.03±0.01	45
D	11.42±0.55	1.12±0.06	10.2
Be	27.30±1.40	6.49±0.37	4.3
C	35.00±1.80	6.64±0.41	5.3
Al	53.10±2.90	13.17±0.90	4.0
Ti	67.00±3.60	21.20±1.60	3.2
Cu	77.30±4.30	25.20±2.0	3.1
Ag	91.60±5.10	35.00±3.0	2.6
Ta	101.00±5.60	51.40±4.70	2.0
Pb	104.20±5.80	53.70±4.90	1.95
Th	107.90±5.90	60.40±5.50	1.9

*D.R.F. Cochran, *et al*, "Production of Charged Pions by 730-MeV Protons from Selected Nuclei", Phys. Rev. D 6, 3085 (1972)

Projections for Fermilab LE Muon Facility

- MTA or a dedicated PIP II facility
  - Not limited to low IL or "light" targets
    - *Both μ^+ and μ^- beams are feasible* (Ta target, for example)
    - Control over primary beam can be "designed in"
  - Timing signals – created by laser-stripping of H$^-$
  - Target R&D (can be started at MTA – proposed LDRD project)
    - Segmented target
      - Increase surface/volume
    - Small targets
      - Backward/90° production
      - larger collection Ω
    - Engineering for high PIP II intensities



R&D: Pion Production with the 400-MeV Linac

Full Linac Capability and Operational Parameters @15 Hz

Parameter	Value	Unit
Kinetic Energy	401.5	MeV
Energy Spread	1	MeV
RF Structure	201.24	MHz
Bunch Length	0.208	ns
Max Pulse Length	80	µs
Max Particles Per Bunch (28 mA) maA	0.88×10^{9}	
Max Particles Per Pulse	1.6×10^{13}	
Peak Current	28	mA
Avg Current	38	µA
Max Beam Power	15.7	kW
Beam Emittance (99%)	8	mm-mrad

- **Pion Production at the MTA**
  - Pion Thresholds
    - Single pion: 280 MeV
  - $p + n \rightarrow p + p + \pi^{-}$ (or π^{+})
    - Pair Threshold: 600 MeV
      - 4 production channels
  - Operational Limits
    - 7.5 x 10^{11} p/sec (average)
    - 20 x 10^{13} p/sec (peak)
- Surface Muon production
  - 10^{-9} μ^{+}/p (C target, 4% IL)
    - assume μ^{-} half of μ^{+}:
    - ~375 μ^{-}/s (average)
    - ~200,000 μ^{-}/s (peak)

Work Plan

- Assemble a team of research and accelerator experts
  - Define physics objectives and associated experiments
    - develop secondary beam specifications
  - Secondary production beamline design (production beamline design expert) to meet beam specifications
  - Production target geometry and material studies
  - Capture optimization studies into secondary beamline
  - Beam simulation, characterization, range of beam properties
  - Community outreach for interest and participation

- Build a nascent collaboration
- Write Contributed Paper

Summary

- A LE muon facility at Fermilab offers immediate and long-term unique science opportunities and capabilities not achievable at other facilities
- "Estimated" Muon Production @MTA
  - With a segmented tantalum target
    - >1000 μ^+ or μ^-/s; cm^2 spot size; 4–100 MeV
      - Instantaneous flux higher
    - Space available for small-scale experiments and target R&D
- *Work is already started on a muon (μ^-)-catalyzed fusion experiment in the MTA hall*
- *PLAN AND INTEGRATE A GREEN-FIELD SITE INTO PIP II*
  - *Work needs to begin/be compatible with PIP II civil planning*
  - *Mu2e infrastructure could be used as a stepping stone*

Letter of Interest for an Upgraded Low-Energy Muon Facility at Fermilab

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• SNOWMASS21-RF0-AF0-007.pdf

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Abstract

A wider variety of world-leading muon beams and experiments can be developed at Fermilab, alongside and following the present g–2 and Mu2e experiments. The MW-scale 800 MeV PIP-II beam is ideally designed to drive a next generation of low-energy muon beams to higher intensities. The Mu2e experiment will be the world's highest-intensity low-energy muon facility, and its beam could be extended to further precision muon studies, both before and after the turn-on of PIP-II. Other experiments could include $\mu \to e\gamma$ and $\mu \to 3e$ searches, muonium studies, and a world-leading muSR facility.

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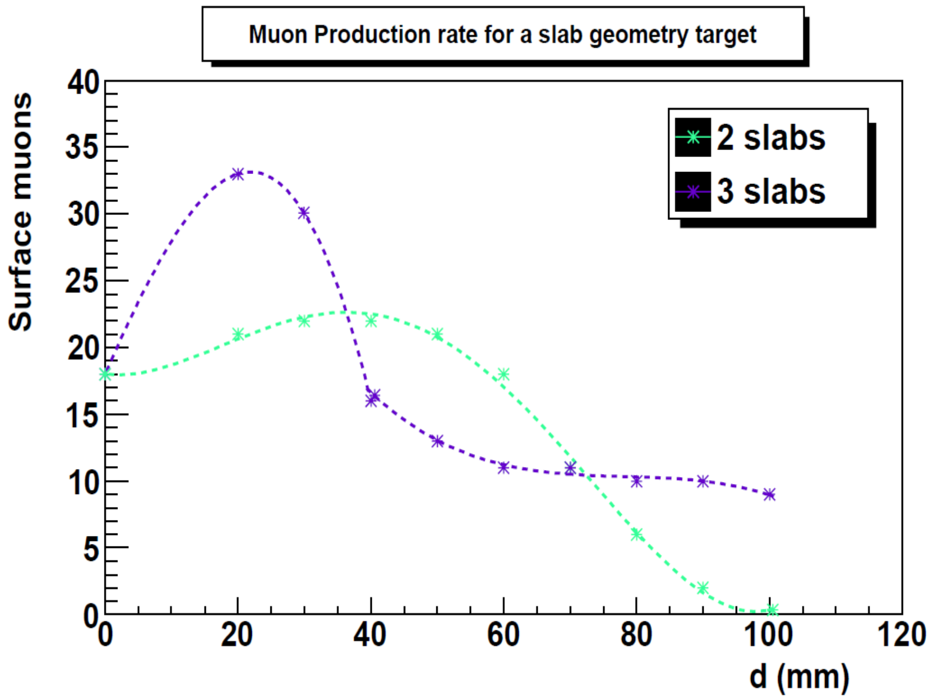
- BACK UP SLIDES

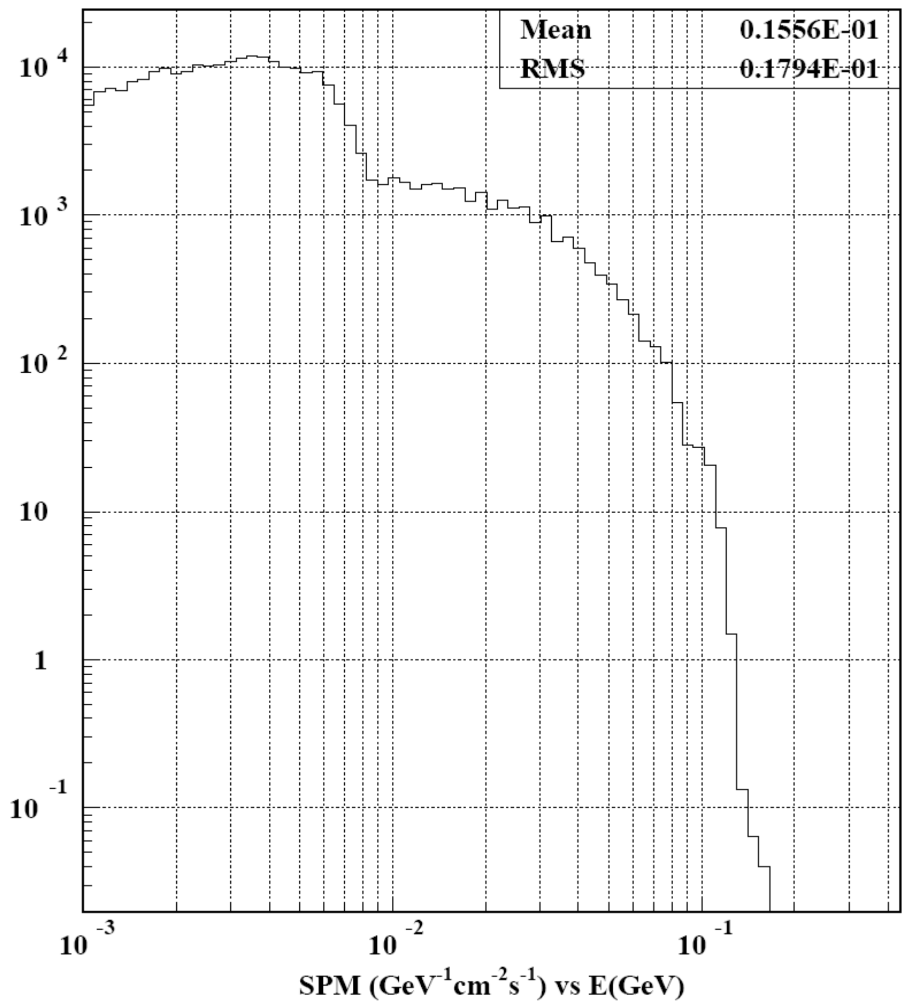
Optimizing Target for μ^-



The number of surface muons collected at the ISIS entrance window to the muon channel beamline with distance showing coupling of target design to muon beamline design.

- Notes:
  - Collection scheme
    - Similar to surface muons
  - Tantalum
    - 2 slices
    - Target angle bisects 135°
  - Capture
    - ~8 cm diameter Al capture window
    - Solenoid recommended
    - Magnets available
      - 8 200-MeV quads
      - 2 Loma Linda quads

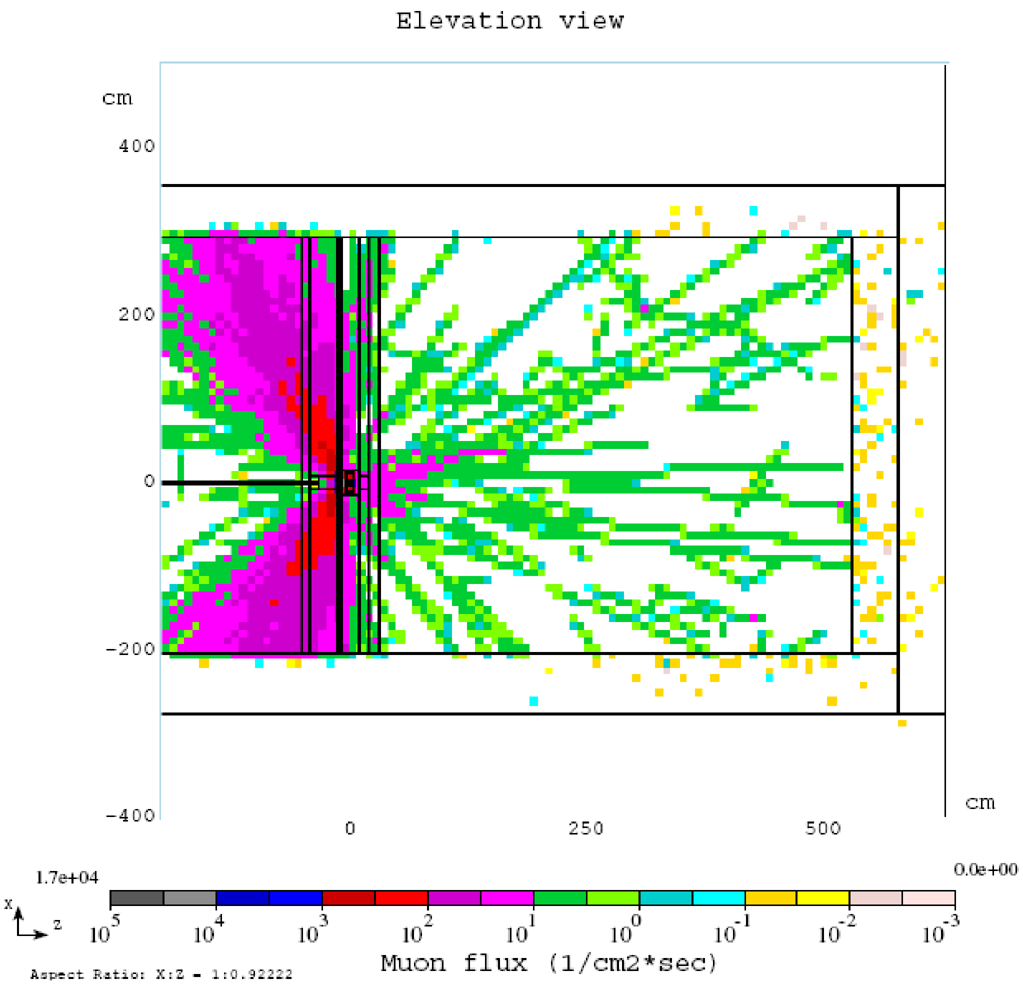
Muon production 2″ steel (MARS run)



Muon energy spectrum from 400-MeV protons incident on a gas-filled RF test cell for 2.67 x 10^{11} p/sec (1.6 x 10^{13} p/pulse and 1 pulse/minute)

- Notes:
  - Average flux
    - Assuming μ^+ plus μ^-
    - Flux integrated over solid angles/area
    - Max rate is 2.8 x higher
    - μ^- rate then is ~1/3
    - Average for 20% IL target
      - ~200 μ^-/sec/cm^2 (steel)
      - ~1500 μ^-/sec/cm^2 (Ta)
  - Energy range:
    - 4 MeV – 100 MeV
  - Depending on directionality
    - Flux likely higher

Muon production on gas RF cavity steel windows



Muon flux in the experimental hall for 2.67 x 10^{11} p/sec (1.6 x 10^{13} p/pulse and 1 pulse/minute in Experiment mode) on a gas-filled RF test cell with thick (>100% Interaction length) walls

- Notes:
  - Production angle backward
    - Higher net flux
    - ~135°
  - Low backgrounds:
    - Forward primary protons
      - ±20° cone

MTA Experimental area and Beamline Stub

Upstream view of Beamline stub

MTA Experimental area and Beamline Stub

Summary

- Estimated Muon Production
  - >1000 μ-/cm^2 average can be achieved
  - 4-100 MeV energy range
  - Instantaneous flux can be much higher
  - For a mm^2 spot size specification – collimation is required
- Tantalum target
  - 2 slices
  - 67° target angle relative to primary beam direction
- Secondary Beamline
  - 135° orientation relative to primary beamline

- Estimated Muon Production (Ta target)

Quantity	Value	Units	Value	Units
Atomic number	73			
Atomic mass	180.94788(2)	g mole^{-1}		
Specific gravity	16.65	g cm^{-3}		
Mean excitation energy	718.0	eV		
Minimum ionization	1.149	MeV g^{-1}cm^{2}	19.14	MeV cm^{-1}
Nuclear collision length	109.9	g cm^{-2}	6.599	cm
Nuclear interaction length	191.0	g cm^{-2}	11.47	cm
Pion collision length	133.4	g cm^{-2}	8.011	cm
Pion interaction length	217.7	g cm^{-2}	13.07	cm
Radiation length	6.82	g cm^{-2}	0.4094	cm
Critical energy	8.09	MeV (for e^-)	7.79	MeV (for e^+)
Molière radius	17.88	g cm^{-2}	1.073	cm
Plasma energy $\hbar\omega_p$	74.69	eV		

- Estimated Muon Production (C target)

Quantity	Value	Units	Value	Units
Atomic number	6			
Atomic mass	12.0107(8)	g mole^{-1}		
Specific gravity	2.210	g cm^{-3}		
Mean excitation energy	78.0	eV		
Minimum ionization	1.742	MeV g^{-1}cm^{2}	3.850	MeV cm^{-1}
Nuclear collision length	59.2	g cm^{-2}	26.79	cm
Nuclear interaction length	85.8	g cm^{-2}	38.83	cm
Pion collision length	86.5	g cm^{-2}	39.12	cm
Pion interaction length	117.8	g cm^{-2}	53.30	cm
Radiation length	42.70	g cm^{-2}	19.32	cm
Critical energy	81.74	MeV (for e^-)	79.51	MeV (for e^+)
Molière radius	11.08	g cm^{-2}	5.012	cm
Plasma energy $\hbar\omega_p$	30.28	eV		
Sublimation temperature (@ 1 atm)	4098.	K	3825.	C